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Major episodes of geologic change: correlations, time structure and possible causes

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ABSTRACT

Published data sets of major geologic events of the past ~250 Myr (extinction events, sea-level lows, continental flood-basalt eruptions, mountain-building events, abrupt changes in sea-floor spreading, ocean-anoxic and blackshale events and the largest evaporite deposits) have been synthesized (with estimated errors). These events show evidence for a statistically significant periodic component with an underlying periodicity, formally equal to 26.6 Myr, and a recent maximum, close to the present time. The cycle may not be strictly periodic, but a periodicity of ~30 Myr is robust to probable errors in dating of the geologic events. The intervals of geologic change seem to involve jumps in sea-floor spreading associated with episodic continental rifting, volcanism, enhanced orogeny, global sea-level changes and fluctuations in climate. The period may represent a purely internal earth-pulsation, but evidence of planetesimal impacts at several extinction boundaries, and a possible underlying cycle of 28–36 Myr in crater ages, suggests that highly energetic impacts may be affecting global tectonics. A cyclic increase in the flux of planetesimals might result from the passage of the Solar System through the central plane of the Milky Way Galaxy—an event with a periodicity and mean phasing similar to that detected in the geologic changes.

1. Introduction

The current plate-tectonic conceptual model implies that all major aspects of the Earth's long-term tectonic regime should be related [1]. The global carbonate–silicate cycle, driven by plate-tectonic processes, provides a direct link between plate motions and ocean/atmosphere composition and climate [2]. A number of studies have shown that patterns of sea-floor spreading have changed in abrupt "jumps" over the past 180 Myr [3,4]. It might, therefore, be expected that these changes would be reflected in the timing of major changes of the coupled geologic/climatic record [1,5,6]. The geologic time scale may provide a record of these major events in the globally recognized boundaries between major chrono-stratigraphic units.

The last 10 years have seen the development of more accurate methods of dating, the fine-tuning of the geomagnetic reversal record and improved correlation based on micropaleontology. Various quantitative tests can be used to determine whether existing data are sufficient to address questions of correlation, and temporal patterns in geologic activity. The value of statistical analysis, of time-series lies in the objective analysis, and quantification, of possible patterns that may not be apparent from the raw data for various reasons, including dating errors, sampling problems, anticorrelations, etc.

Some workers [e.g., 7] believe that tests of the time structure of the geologic record should be postponed until better data become available. In general, however, these studies have not attempted to assess statistically the reliability of existing geologic data. Baksi [7] also seems to

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infer that the detection of periodic components in time series demands a strict periodicity of the events, which is not the case. His conclusion that no periodicity was present in flood basalts was based partly on the fact that the two Indian flood basalts he studied were not exactly 26–30 Myr apart [7]. The results of a number of recent investigations (see below) indicate that geologic data have improved to the point where quantitative methods can now be brought to bear in testing well-posed hypotheses.

We believe that such studies are crucial, since an accurate time history of major geologic events, and of any patterns therein, must be acquired before one can hope to understand the underlying causes of geologic activity. For example, we note that this has proven true in studies of climate change (e.g., the Milankovitch cycles) and in the application of the geomagnetic reversal time scale to the problem of sea-floor spreading.

2. Data collection and synthesis

2.1. Rationale

We have gathered (based on a page-by-page examination of major geological journals back to 1975) coherent data sets of discrete times of occurrence of various major geologic events of the last 250 Myr. Our survey has produced the seven independent sets of data listed in Table 1 (where the dates have been placed in 10 Myr bins). Intercomparisons of these data with similar data from other sources, using several of the most recent geologic time scales for dating, show a consistency in the recognition and dating of many of the critical events in the last ~ 250 Myr of earth history.

A comparison of current geological time scales [8] shows a considerable agreement among the dates of stratigraphic boundaries in the Meso-

TABLE 1

Compiled data of the dates of important geologic changes during the last ~ 250 Myr. Dates in m.y. ago. See text for sources

Date	Mass extinctions	Anoxic events	Evaporite deposits	Flood basalts	Sea-floor spreading	Sequence boundaries	Orogenic events
0– 9	1.6		5		2		0.6, 2.5, 4, 5
10– 19	11.2			17	10, 17	16	12.5
20– 29							25
30– 39	36.6		36.6	35		30, 36.6	
40– 49					40		40
50– 59					53	52	
60– 69	66			62, 66	63	60.6	65
70– 79					77		
80– 89		84				86, 88	80, 87
90– 99	91	91		92	94	97	
100–109							100
110–119	113	113		110	112	113	
120–129							
130–139				130, 135		138	
140–149	144		144		148	144	145
150–159		156				154	155
160–169		163					
170–179	176			170		173	
180–189							
190–199	193	193		190		196	
200–209		208	208	200		208	
210–219	216						
220–229						220	220
230–239						230	
240–249	245	245					
250–259			258	250			250

zoic–Cenozoic. In geologic time scales published in the last 10 years, the average disagreement for stage boundaries is ~2% within the Tertiary, ~3% in the Cretaceous, ~3% (7% if one includes dates from the Salvador [9] time scale) in the Jurassic, and ~6% during the Triassic. Agreement, however, does not necessarily mean accuracy, and sections of the record (e.g., the Jurassic) are often quoted with large formal uncertainties (~20%) because of lack of absolutely dated tie points. However, independent analyses indicate that these large uncertainties may be unrealistic and misleading [10]. One significant problem involves the definition of the Jurassic/Cretaceous boundary at the beginning (144 Myr) or end (138 Myr) of the Berriasian stage [11].

A possible problem in a study of this kind, however, concerns conscious or unconscious subjectivity and bias in choosing data sets for analysis. For the present study, we have intentionally refrained from making changes in any of the published data sets. This means that, in a number of cases, the dates that we use here may not constitute what we consider the "best" date for a specific event based on ancillary studies. However, in each section below we will discuss possible changes that we believe could be made to improve the quality of the data sets used.

We have tried to use the most recent and/or most complete data sets available. Note also that the data sets are a mixture of stratigraphic and radiometric age determinations. In cases where stratigraphic information was clearly being used in the dating (extinctions, sequence boundaries, anoxic events, evaporites), events were re-dated here for consistency using the Palmer–DNAG time scale [12]. The same data, however, have been examined using other time scales, as well (see below).

2.2. Data sources and reliability

Extinction events: The state-of-the-art data set for diversity of marine organisms is the compilation of stratigraphic ranges of genera by Sepkoski. Dates of biologic extinctions listed are for all 11 peaks in the per-genera extinction rate based on all 17,500 genera in the latest (1989) Sepkoski data set [13, fig. 2; and pers. commun., 1991] for 49 (substage) sampling intervals, with the dating here after the DNAG time scale [12]. Use of substage sampling overcomes previous criticisms that stage lengths of ~6 Myr might be creating a spurious period in mass extinctions [13]. We chose this extinction data set because it is the most up-to-date, conservative and complete available, and in this form does not contain any selection of the recognized extinction events according to estimated severity.

Stratigraphic sequence boundaries: Vail et al. [14] proposed that widely recognized sequences of sediments, bounded by unconformities, represented units with chronostratigraphic significance, controlled primarily by global changes in sea level. Seismic-reflection studies from various continental margins and sedimentary basins were used to develop a record of global cycles of sea-level fluctuations based on the stratigraphy of depositional sequences. In seismic sections, sequence boundaries are expressed by the basinward shift of coastal onlap. In outcrop, a sequence boundary may be represented by more subtle changes, depending on the position of the section along the shelf-to-basin profile, and on the rate of relative sea level fall. Significant sea-level falls are manifested by prominent unconformities, with erosional truncation caused by subaerial exposure. Sequences and sequence boundaries are classified as major, medium and minor. Only sequences of major and medium magnitude are discernible at the regional seismic level, whereas minor sequence boundaries can be resolved in outcrop sections [14].

The present state-of-the-art global compilation is that of Haq and co-workers [15], who list 21 major sequence boundaries for the last 260 Myr. Times between major sequence boundaries vary from 2.5 to 25 Myr, with a mean spacing of 12.2 Myr [15]. The most recent detailed study is that of Hubbard [16] of rifted margins in the North Atlantic, South Atlantic and Arctic Oceans. He believes that sequence boundaries may also be the result of interactions between tectonism and sedimentation, especially along active margins, but is generally uncommitted to a particular interpretation. Hubbard's more neutral data has been used here, re-dated using the Palmer–DNAG chronology.

Continental flood basalts: Continental flood basalts represent the largest outpourings of mafic magma. They are an order of magnitude or more greater in volume than the next largest provinces of basalt eruptions. Recent studies suggest that eruption of most of the basalts takes place within 2–3 Myr at most [17]. Estimated dates of initiation times of eleven recognized major continental flood-basalt episodes were taken from the compilation of Rampino and Stothers [17]. These data are absolute ages based on more than 900 published radiometric and isotopic age determinations, and represent the most complete collection of flood-basalt age determinations to date. Stratigraphic and paleomagnetic age data were used only as an adjunct to the radiometric dates. Conservative error estimates in [17] ranged from ± 1 million years for the Columbia River Basalts (17 m.y. ago) to ± 10 Myr for the Siberian Traps (~ 250 m.y. ago), with the initiation times of most flood basalts having an estimated error of ± 5 Myr.

Recent studies, using more accurate $^{40}Ar/^{39}Ar$ and U/Pb dating methods, allow a refinement of these initiation dates. For example, the Siberian Traps have been dated by $^{40}Ar/^{39}Ar$ techniques at 248.4 ± 2.4 Myr [18]. New $^{40}Ar/^{39}Ar$ age determinations for the Serra Geral Basalts suggest an age of 132 ± 1 Myr (C. Hawkesworth, pers. commun., 1991) and the Antarctic (Ferrar) basalts are dated at 176 ± 1 Myr [19]. Tholeitic basalts in West Africa yield $^{40}Ar/^{39}Ar$ ages of 203.7 ± 1.7 Myr [20]. An additional continental flood-basalt, the Madagascar Basalts, estimated to be Cenomanian to Turonian in age ($\sim$ 85–90 Myr), is now believed to have been much more widespread [21] and is included here as a true flood basalt. Subsequent to our analysis, the Wrangellia Flood Basalt (probably largely oceanic) [22] has been identified and dated as close to the Ladinian–Carnian boundary (230 Myr), which correlates with a number of other mid-Triassic events listed in Table 1. We have not yet revised our analysis using this date, even though it would most likely improve our statistical results. Large oceanic plateaus [23–25] are interpreted by some as being the result of oceanic flood basalt eruptions. They are in general poorly dated, however, and are not included in the present analysis, although the Ontong-Java Plateau has now provided $^{40}Ar/^{39}Ar$ ages of about 117 to 121 Myr [23,25].

Orogenic episodes: Stille published early lists of orogenic episodes, which he defined as discrete events that produced large-scale structural deformation of strata [26,27]. In the modern definition, orogeny is usually considered to include deformation, magmatism and regional metamorphism. The classic method used to date an orogenic event is to bracket it between the ages of deformed and undeformed strata [28]. Stille argued that the major periods of deformation represented events that took place roughly synchronously in widely separated areas, although each episode was strongest only in certain mobile belts. In the modern plate-tectonic interpretation, this might suggest periods of rapid spreading and plate convergence, with arc and continental collisions only along some susceptible boundaries.

The idea of orogenic "episodes" was eventually rejected in favor of essential uniformity in global tectonism [29]. Damon [30], however, found that orogenic episodes could be defined by peaks in histograms of radiometric age determinations, and that groups of Stille's episodes over the last 600 Myr correlated well with independently determined times of marine regression. Furthermore, these episodes have long been used in helping to define geologic boundaries. Thus, the question of a global episodicity in orogenesis remains open. For the present study, we infer that the orogenic episodes are of, at least, broad regional significance.

We have taken the dates of purported major orogenic episodes as those listed in the latest edition of the Geologic Time Table compiled by Haq and Van Eysinga [31], as these represent a widely disseminated and "neutral" set of data. The episodes listed are (in million years ago): Wallachian 0.6; Pasadenean 2.0; Rhodanian 4.0; Attican 5.0; Styrian 17.5; Savian 25; Pyrenean 40; Laramide 65; Sevier–Columbian 80; Subhercynian 87; Oregonian 100; Late Kimmerian 145; Nevadan 155; Early Kimmerian 220; Appalachian 250.

No error estimates are given in the Time Table itself, but these dates can be considered good to within the stage or stages in which the deformation has been bracketed [28]. These episodes and their approximate dating are borne out by other related compilations of orogenic episodes [32,33]. Damon roughly estimated that orogenic "pulses" (which may contain more than one episode) had an average duration of about 8 Myr [30]. However, interpretation of orogenies as extended events is based in large part on K–Ar age determinations that are known to show wide ranges as a result of Ar loss. Recent detailed studies, with less problematic dating techniques, support the idea that orogenies may be characterized by brief, abrupt events lasting < 5 Myr [34,35].

As a result of the thermo-tectonic nature of orogenesis, it is possible that large compilations of radiometric age determinations of igneous and metamorphic rocks can be used as proxies for times of orogenic activity, provided that problems, such as Ar loss in K–Ar dating, are taken into consideration. Such a compilation has been attempted for the Precambrian, resulting in the delineation of possible major worldwide orogenic phases [36]. For more recent times, a new summary of more than 6,000 Late Mesozoic to Late Cenozoic age determinations for the western United States [37] shows well-developed peaks in the ranges 30–40 m.y. ago, and 65–75 m.y. ago (= Laramide event), and a compilation of Mesozoic radiometric ages from Japan shows distinct peaks at ~ 60, 90 and 120 m.y. ago [38]. Unfortunately, a global compilation of the best age determinations for the last 260 Myr is not available as yet.

Sea-floor spreading: Studies of marine magnetic anomaly patterns, age determinations of ocean crust, and trends in linear island/seamount chains, have recognized significant changes in the pattern of sea-floor spreading, typically related to "jumps" in spreading centers. The dates of recognized major discontinuities in global sea-floor spreading (sometimes described vaguely as "plate reorganizations") were taken from a summary paper by Schwan [39] (using data from original papers on sea-floor spreading patterns interpreted from marine magnetic anomalies), with an additional, recently identified, spreading discontinuity in the Pliocene [40]. Data compiled independently by us from a number of other sources give essentially the same dates for widespread spreading discontinuity events [3,4,41,42].

Small differences in dating among published studies are largely due to the rounding off of dates and/or the differences in geologic time scales. For example, the events that define the limits of the Cretaceous period of rapid spreading are dated by Schwan as 115 and 80 m.y. ago, and by the DNAG scale as 118 and 84 m.y. ago, differences of only 3–5%. These dates were not established on the basis of stratigraphic stage boundaries, so we did not re-date the original data set (Table 1).

Ocean anoxia: Times of open ocean "anoxic" and/or widespread black-shale events on the platforms are from a recent compilation by Leary and Rampino [43], which came out of the present search of the relevant literature, dated with the Palmer–DNAG time scale. An additional anoxic event, not included in the published compilation because of its possible regional nature, was added

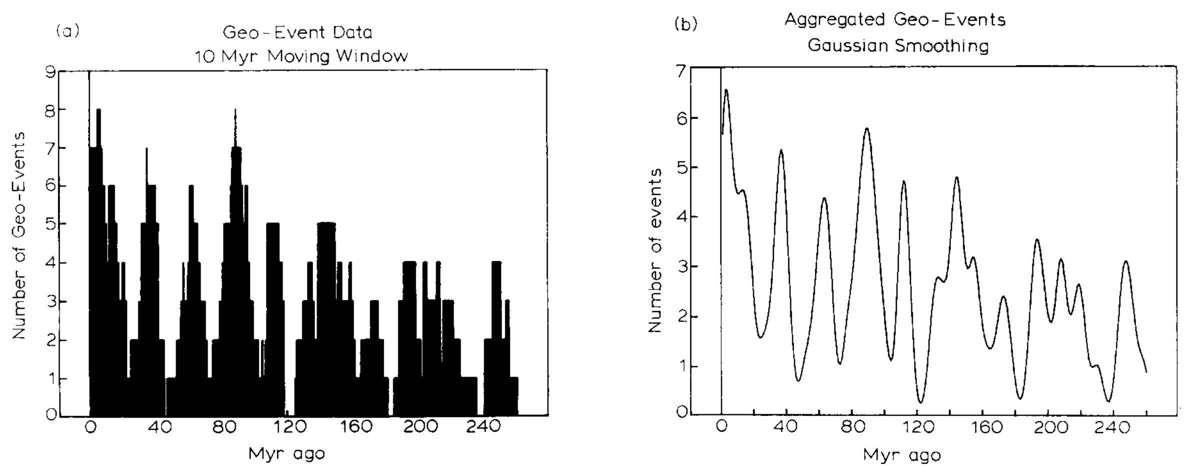

Fig. 1. (a) Number of geologic events listed in Table 1, within a 10 Myr moving window as described in text. (b) Number of geologic events, weighted by a Gaussian function with a scale length of 5 Myr.

in the Coniacian–Santonian [44], dated at 84 ± 4.5 m.y. ago (end-Santonian) based on new information (M.A. Arthur, pers. commun., 1991). These intervals correlate well with times of positive excursions of $\delta^{13}C$ in pelagic carbonates, indicating times of increased accumulation of organic carbon-rich deposits [45].

For consistency, and to avoid interpolation between dated stage boundaries, the anoxic events that may occur across more than one stage were assigned to the intervening stage boundary—this produces only small changes in the ages. Estimated errors are those associated with the stage boundaries [11].

Evaporite deposits: Epochs of the major global evaporite deposits come directly from Ronov [46], the only such global compilation available, and are here re-dated after Palmer–DNAG. We realize that this short data set may actually have a negative effect on the significance of our results, but include it because of its possible relationship to rifting events, and to be on the conservative side.

3. Statistical testing and results

3.1. Time-series analysis

Moving-window analysis: Initially, a 10-Myr moving-window, centered every 0.5 Myr, was applied to the combined age data of the various phenomena and the number of dated occurrences that fell within the moving window was computed at 1-Myr intervals (Fig. 1a). The results show peaks in the number of dated events: between the peaks the number of geological events drops off sharply and commonly reaches zero. In order to test the effects of window size on the location of these peaks, we used varying moving windows from 2 to 15 Myr. The peaks remained stable in position despite variations in the size of the moving window.

Gaussian filtering and high-frequency noise: A second independent method was to treat each date in the record as a delta function (spike), and then to apply a Gaussian smoothing function with a scale-length of 5 Myr to the resultant function. The Gaussian filter removed high-frequency noise components (Fig. 1b).

Fourier analysis: We computed the Fourier transform of the auto covariance function of the original un-windowed time-series data, rounded to the nearest million years, utilizing a standard Tukey window with a bandwidth of 4.5 Myr [47]. The highest peak in the Fourier power spectrum occurs at a period of 26.6 Myr (Fig. 2). The Fourier transform of the time-series data suggests a phase with the most recent maximum of the 26.6 Myr cycle occurring about 8.7 m.y. ago. We note, however, that the detection of a possible 26.6 Myr period does not rule out the presence of longer or shorter periods in the geologic record.

An indication as to the significance of the result can be obtained by comparing the computed Fourier transform with the Fourier transform of pseudo-data sets with similar statistical properties. To do this we computed the Fourier transform of 1,000 pseudo-data sets each contain-

TABLE 2

Geologic events, with dominant periods (listed in the order in which they add power to the 26.6 Myr spectral peak of the aggregate), phase, and spectral power at 26.6 Myr. Dominant spectral peaks for each type of geologic event are listed in order of spectral power

Geologic events	Dominant period of events (Myr) [1]	Dominant period of aggregate-events	Phase at 26.6 Myr	Power at 26.6 Myr
Extinctions	<u>26.0</u>	26.9	9.0	0.94
Sequence boundaries	<u>28.2</u>	26.5	9.3	0.73
Flood basalts	<u>23.1</u>, 15.4, <u>26.2</u>	26.7	9.5	0.53
Orogenic events	<u>30.6</u>	26.2	8.4	0.24
Sea-floor spreading	18.4, <u>26.7</u>	26.6	9.8	0.07 [2]
Ocean anoxic events	39.7, <u>26.1</u>	26.9	3.6	0.37
Evaporite deposits	<u>28.2</u>	26.5	11.7	0.04 [2]

[1] In order of greatest power, underlined periods are those contributing to 26.6 period of aggregate.

[2] Too few events for highly significant results.

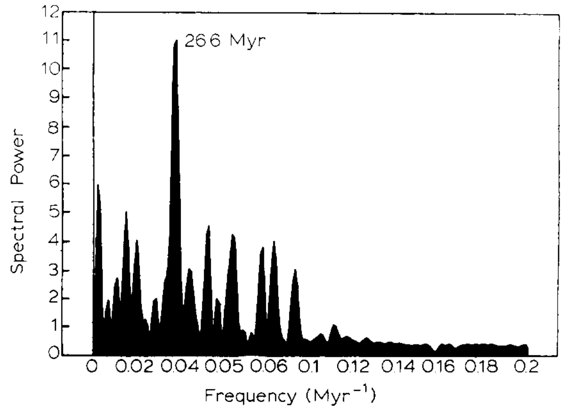

Fig. 2. Spectral power for all data sets, computed as described in text directly from the data in Table 1. The highest peak is at a period of 26.6 Myr.

ing the same number of randomly dated pseudo-events over the same time-interval (0 to 260 m.y. ago). Based on analysis of the 1,000 pseudo-data sets, we conclude that the probability of randomly generating higher spectral power at 26.6 Myr is about 0.01%, and the probability of generating higher spectral power in any period between 10 and 65 Myr is about 4.5%.

3.2. Tests of robustness of the possible period

We tested for the robustness of the inferred period in several ways. Initially, we re-analyzed the data while eliminating each type of geologic event from the aggregated record one at a time (Table 2). When this was done, the dominant period remained at 26.6 ± 0.4 Myr, which emphasizes the fact that this period is not dependent upon any one particular type of geologic event. It is noteworthy that the dominant period of the geologic events minus the extinction events removed (26.7 Myr) is close to the strong periodicity seen in the extinction events themselves (25.9 Myr) (Fig. 3a). Sequence boundaries show a spectrum with strong peaks at 28.3 and ~ 60 Myr (twice the 28.3 Myr period) (Fig. 3b). In the higher-frequency portion of that spectrum, peaks occur at periods of 11.2 and 12 Myr. When only the extinction and sequence-boundary data sets are combined and analyzed, the result is a very strong peak at 26.2 Myr, whereas the other peaks become much weaker or disappear (Fig. 3c).

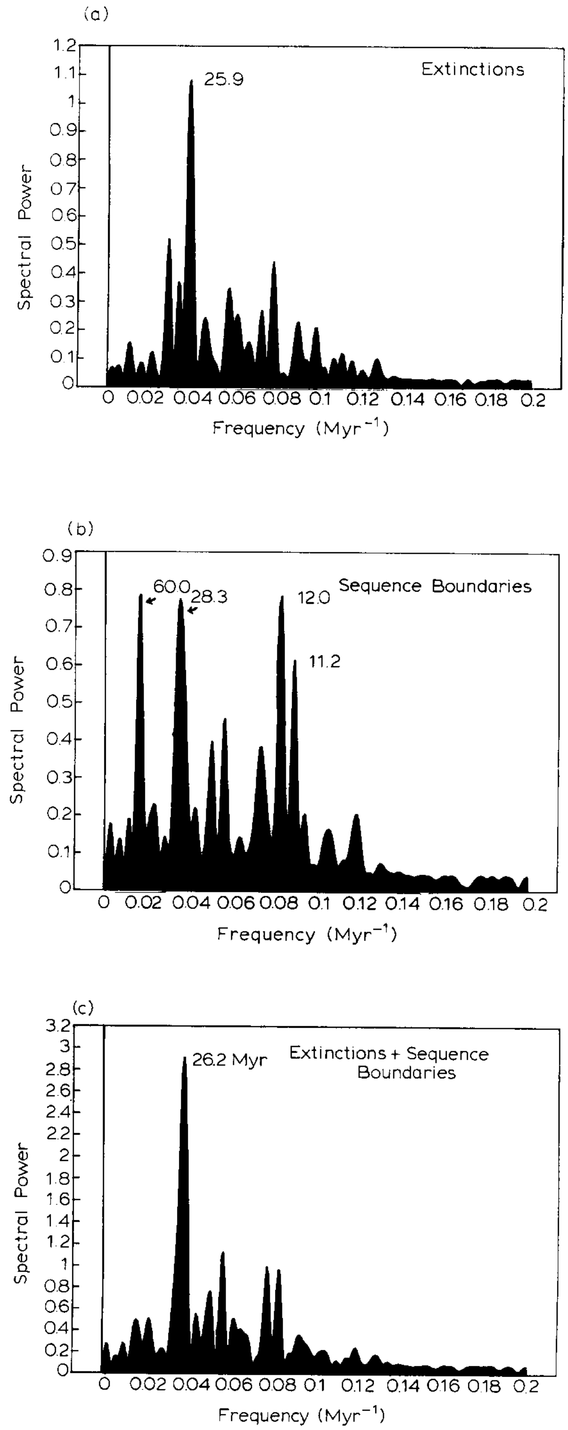

Fig. 3. (a) Power spectrum of eleven extinction events. The highest peak is at a period of 25.9 Myr. (b) Power spectrum of stratigraphic sequence boundaries. Note highest peaks at periods of 28.3 and 60.0 Myr. (c) Power spectrum of combined extinction events and stratigraphic sequence boundaries. The highest peak is at a period of 26.2 Myr.

The remaining five aggregated data sets display a relatively weak signal at around 26 Myr, with a strong peak at 52 Myr in the power spectrum that might reflect the incompleteness of these data. This shows that most of the power seen in the aggregate at 26 Myr comes from the extinction and sequence-boundary data (Table 2), as these constitute $\sim 40\%$ of the data points in the analysis, and are the most complete data sets used. The weaker 26 Myr periodicity seen in the five other data sets might reflect, at least partially, the lesser number of events in those compilations. It is important to note, therefore, that the results of the moving window analysis show that these geologic events tend to cluster episodically with the extinctions/sequence boundaries over the last 260 Myr, and thus seem to be following a similar time history.

The phase for each event type at the period 26.6 Myr was determined by computing the complex Fourier transform of the Gaussian filtered time-series data (Table 2). The most recent maximum in the 26.6 Myr harmonic for extinctions, sequence boundaries, flood basalts, orogenic events and sea-floor spreading events in the last ~ 250 Myr falls in the range of 9.1 ± 0.7 m.y. ago (formal error). However, the specific value obtained for the phase seems to be significantly affected by the fact that the most recent part of the event record is actually composed of two overlapping peaks—one very close to the present time, and the second at about 16–17 m.y. ago (Fig. 1a). These two peaks (or sub-peaks) apparently contribute to the determination of a mean phase of about 8 to 9 m.y. ago for a 26.6 Myr period.

3.3. *Effects of dating errors and geologic time scale on results*

Could some inherent or spurious periodicity in the geologic time scale [48–52] tend to bias the analysis? Inaccurate dates or misplaced events should act to degrade the sample in a direction toward randomness, and away from any regular signal [52] (although, for data covering a small number of cycles, a false period might be introduced). The inclusion of less accurate data should make the statistical testing more, not less, conservative. Raup and Sepkoski [50] estimated the effect of the structure of the geologic time scale on detection of periodicity in extinctions, and found that the Harland-1982 time scale [33] introduced only a small bias towards a best-fitting period of 26 Myr. Stothers [10] discovered a weak 28 Myr period in the Palmer–DNAG time scale used here. For the Harland-1982 time scale, Stigler and Wagner [52] concluded that the non-linear interpolation of stage lengths in the Mesozoic (6, 6, 6 and 7 Myr, equal to 25 Myr, repeated several times) contributes strongly to the preference for a 26 Myr periodicity seen in the time scale itself. They found, however, that if such non-linear interpolation of stage lengths was avoided, and a few other minor changes in the time scale were made, the preference for a 26 Myr period disappeared [52].

The latest Harland-1989 [53] time scale has Mesozoic stage lengths that vary from 0.8 to 13.9 Myr. Fourier analyses of the stage boundaries over the last 245 Myr shows a spectral peak at 30 Myr, but no preference for a periodicity of 26–27 Myr. In order to test the possible dependence of periodicity on the particular time scale used further, we repeated the time-series analysis on the geologic data in Table 1 after re-dating all stage-boundary events using the Harland-1989 time scale. We detected a statistically significant periodicity of 26.7 Myr, with the most recent maxima of this harmonic at 8.2 m.y. ago, which represents only a very slight shift in the dominant period and phase from the analysis using the Palmer time scale. As we detect the same ~ 27 Myr periodicity in geologic events when using the Harland-1989 time scale, and no peak at 30 Myr, we infer that the period seen in the geologic data is probably not merely an artifact of the time scale.

The "geologic time scale": We have discussed the geologic time scale in the context of Stigler and Wagner's criticisms [51,52]. However, there is a larger issue that they, as non-geologists, apparently did not fully recognize. The "geologic time scale" is not an arbitrary measure of geologic time, but a chronology of the major changes, or signposts (e.g., extinctions, stratigraphic sequence boundaries, unconformities produced by orogenies, etc.) in the geologic record. Chronostratigraphic boundaries were not chosen arbitrarily, they represent natural subdivisions of geologic time—times of significant changes. The utility of a single basic global geologic time scale, with well-recognized boundaries, and the fact that intercontinental correlations can be routinely made on the level of the geologic stage, points to the existence of widespread geologic events. Therefore, detection of periodic components in the ages of some boundaries in the time scale might well reflect real periodicities or quasi-periodicities in the geologic record itself.

4. Discussion

The correlation of extinctions with other geologic events is not unexpected. Extinction episodes have traditionally been associated with terrestrial geological events, including sea-level fluctuations, enhanced volcanism, orogenesis, climate change, ocean anoxia and ocean-salinity variations. For example, Rich et al. [4] found a good correlation between fluctuations in sea-floor spreading rates and marine biologic diversity, and outlined a chain of plausible cause-and-effect relationships.

Raup and Sepkoski [54] originally identified 12 extinction events at the family level over the last 250 Myr and reported a 26.4 Myr periodicity in the extinctions, with the most recent maximum of the cycle at 10 m.y. ago. Rampino and Stothers [55] reported a period or quasi-period of 30 ± 1 Myr for the nine most severe extinction events. Periods of 26 to 31 Myr have been derived using different subsets of extinction events (family and genus levels), different time scales and various methods of time-series analysis [13, 55–59], although, as discussed above, the regularity, statistical significance and reality of the dominant periodicity are subjects of debate. Extinctions of non-marine tetrapods seem to follow a similar 29–33 Myr periodicity [60].

The possibility of a ~ 30 Myr pulse in the geologic record has long been recognized [see review of early work in 60]. Using a linear time-series analysis technique, a period of 33 ± 3 Myr [55] was detected in the timing of eighteen orogenic events of the last 600 Myr. Compilations of radiometric ages of kimberlite and carbonatite intrusions over similar intervals showed weaker periodicities of ~ 35 and ~ 34 Myr, respectively.

Major sea-floor spreading events over the last 180 Myr, and sea-level fluctuations, in the form of the extreme low sea-level stands from the "Vail Curve" over the past 200 Myr, both revealed a possible underlying periodicity of about 33 Myr [55]. A Fourier analysis of the more recent Haq et al. [15] sea-level curve also shows a strong 33 Myr cycle [61]. Our own analysis of all 21 major sequence boundaries given in [15] for the last 200 Myr shows a strong spectral peak at 34.5 Myr. A possible 30 Myr period has also been detected in the initiation dates of flood-basalt eruptions [17]. Recently, oxygen-isotope records of climate for the past 130 Myr were found to show a periodicity of about 30 Myr [62]. Several independent analyses of geomagnetic reversals over the last 165 Myr give a spectral peak at about 30 Myr [63–65], although the statistical significance of this peak has been disputed [66,67].

5. Possible causes of an underlying cycle

5.1. Internal causes

Our preliminary results support a model in which rapid "jumps" in sea-floor spreading and outbreaks of hotspots (flood basalts) are related to rifting, volcanism, orogenesis, oscillations of global sea level and changes in the composition of the Earth's atmosphere and oceans, especially atmospheric carbon dioxide, through perturbations of the carbon cycle. This is similar to Sheridan's "pulsation tectonics" scenario [68,69].

The apparent tectonic oscillation could be solely a result of internal core/mantle dynamic processes, which may affect the geomagnetic field as well [70,71]. Loper and co-workers [71,72], for example, suggested that mantle plumes could lead to such correlated episodes of geologic activity. Time-dependent numerical models of thermal convection in the Earth's mantle suggest that at high Rayleigh number, the route to chaotic thermal convection in the mantle may be through periodicity and quasi-periodicity [73,74]. Ridge "jumps", however, may be too rapid to be caused directly by convective plumes. The rapid changes in spreading patterns might be related to sudden changes within oceanic slabs sinking into the mantle [75]. Alternatively, the driving force for the tectonic oscillations might be a result of the changing configuration of the Earth's plates [76,77].

5.2. External forcings

A number of extinction events have been found to be associated with stratigraphic evidence of large-body impacts (shocked minerals, tektites/microtektites, and iridium anomalies) [78–81]. A possible scenario involving a combination of internal and external forcings, outlined by Sepkoski [82], proposes an internally generated ~ 30 Myr period in the Earth's tectonism and climate, with random extraterrestrial impacts that sometimes greatly amplify the roughly periodic oscillations in environmental stress.

Planetesimal impacts, however, represent the most energetic events that can perturb the Earth [83]. An ~ 10 km diameter impactor (which are estimated to strike the earth at a rate of ~ 1 every 20–100 million years [84,85]) provides a total of at least 10^{24} J, with ~ 0.01%, or 10^{20} J going instantaneously into seismic energy (eventually dissipated as heat). This is 100 times greater than the yearly release of terrestrial seismic energy (~ 10^{18} J), and the rate of energy input (~ 10^{20} J s^{-1}) is ~ 10^7 times the rate of global heat flow. The impact seismic energy is equivalent to a magnitude 11–12 earthquake, with oscillating ground motion of hundreds of meters even ≥ 1,000 km from an impact site [83].

Time-series analyses of terrestrial impact craters [55,56,86,87] suggest a possible ~ 30 Myr periodicity. The cratering record may be composed of a combination of periodic and random components. The most recent maxima of the periodic component varies from 13 ± 2 m.y. ago (for a 28.4 ± 1 Myr cycle) to 2 ± 2 m.y. ago (for a 32 Myr cycle). The phasing, however, depends on the deletion or inclusion of large craters less than 5 Myr old in the analysis, and hence may be analogous to the split peak in recent geologic events at ~ 16 and ~ 2 m.y. ago. The presence and significance of the detected periodicity in cratering have been questioned by Grieve et al. [88], although this analysis actually shows an ~ 36 Myr period significant at the 2σ level. The most recent work suggests that the periodicity may be robust even under rather stringent criteria [87].

An astronomical pacemaker? A possible pacemaker for periodic impacts may exist in the Solar System's vertical oscillation above and below the central plane of the Milky Way Galaxy. The dominant underlying periodicity detected in the geologic record is similar to the interval between the times when the Solar System crosses the galactic plane (31.5 ± 1 Myr for the most conventional galactic models, although alternative models give intervals ranging from 26 to 36 Myr [89]). The estimated time of last plane crossing < 3 m.y. ago [89], matches the last extinction event 2.3 m.y. ago [13]. The Solar System's Oort Cloud of comets might be disturbed by gravitational effects of interstellar clouds in the plane region [85,90], or perhaps by tidal distortions generated during plane crossing [M. Valtonen, pers. commun., 1991], causing an increase in the number of comets entering the inner Solar System, and leading to possible pulses of large-body impacts on Earth.

Further support for the importance of external agents in earth history comes from recent work suggesting that diamictites and related deposits in the geologic record that have been interpreted as tillites—ancient glacial deposits—may in reality be debris-flow ejecta of large impacts [91,92].

6. Conclusions

The analyses reported here, combined with previous studies, provide evidence that major geological events may occur in correlated episodes and that these episodes have a periodic component with an underlying periodicity ranging from ~ 26–36 Myr (simple mean = 31 Myr). We suspect that this might represent a single underlying period: the range of period length could indicate only a quasi-periodicity (with a well-defined mean cycle time), or perhaps a strict periodicity, with the range in the specific periods detected resulting from sparseness of data, dating uncertainties, record-length effects, the use of different geologic time scales and other variables. The cause of the possible ~ 30 Myr cycle might be a regular oscillation of internal Earth activity, an external forcing related to periodic comet/asteroid impacts, or some combination of the two. We find it intriguing that the periodicity detected here and elsewhere is close to the half-cycle of the vertical oscillation of the Solar System with respect to the plane of the Galaxy.

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